Future Directions in DARPA's Materials Programs

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Good morning. Materials and materials processing have been a traditional strength of DARPA and of the Defense Sciences Office for over 30 years, with a tremendous impact on weapons and weapon systems. In the next half hour I will describe some of the trends emerging within the DoD and their implications on materials and materials processing programs at DARPA.

Outline

Program Overview

New Paradigms for Materials R&D

“Smart” Materials and Structures

Novel Materials Structures

Summary

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The DARPA Materials Program is a very diverse and dynamic program. This talk will provide an overview of that program and some of the rationale for its current direction. It will also highlight some of the new approaches being taken for materials R&D at DARPA. Finally, the technical highlights of the program will be presented with an emphasis on those areas which have new opportunities.

DSO Materials Program

DARPA

Structural Materials	Ceramics, Metals, Composites	Ceramic Matrix Composites; Ceramics Insertion; Ultra-lightweight Metals
	Devices and Structures	Personnel Protection; Mesoscopic Machines; Solid Freeform Fabrication; Rapid Prototyping; Thin Film Coatings
	"Smart" Materials	Sensors; Actuators; Integration; Demonstrations
	Optical Materials	Compact Lasers; Precision Optics; Holographic Data Storage
	Power Materials	Fuel Cells; Thermoelectrics; Photovoltaics; Thermophotovoltaics; Energy Harvesting
	BioMaterials	Biomimetics; Tissue Based Sensors; Electronic Dog's Nose
Functional Materials	Electromagnetic Materials	Magnetic Materials; Cryosystems; High Power Electronics; Thin Film Diamond; High Density Packaging

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This chart depicts the full range of DARPA's materials program. As can be seen, the programs range from purely structural to purely functional. Stu Wolf will describe in detail the efforts in electromagnetic materials; Bob Nowak will describe the efforts in power systems and materials. Therefore, this talk will focus on the other components of the program, with an emphasis on where the emerging opportunities are.

DSO Materials Program

DARPA

Structural Materials	Ceramics, Metals, Composites	William Coblenz, C. Robert Crowe
	Devices and Structures	Steven Wax, William Warren, William Coblenz, Kevin Lyons
	"Smart" Materials	C. Robert Crowe, Wallace Smith
	Optical Materials	L.N. Durvasula
	Power Materials	Robert Nowak, Steven Wax
	BioMaterials	Alan Rudolph, Regina Dugan
Functional Materials	Electromagnetic Materials	Stuart Wolf, Francis Patten, Steven Wax, Jane Alexander

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This chart depicts the program managers who are responsible for various aspects of the program. Please feel free to contact any one of these program managers.

Critical Elements of DARPA's Materials Program (Examples)

DARPA

Support Emerging DoD Trends

- Force Projection, Mobility
- Littoral Operations
- Information Driven Warfare
- Aging Platforms
- Small Units, Urban Warfare
- Unmanned Systems
- Nuclear/Chem/Bio Threat

Exploit New Concepts in Materials Development

- Rapid Design and Prototyping
- Micro/nanostructure Control
- Computational Materials Science
- Combinatorial Synthesis

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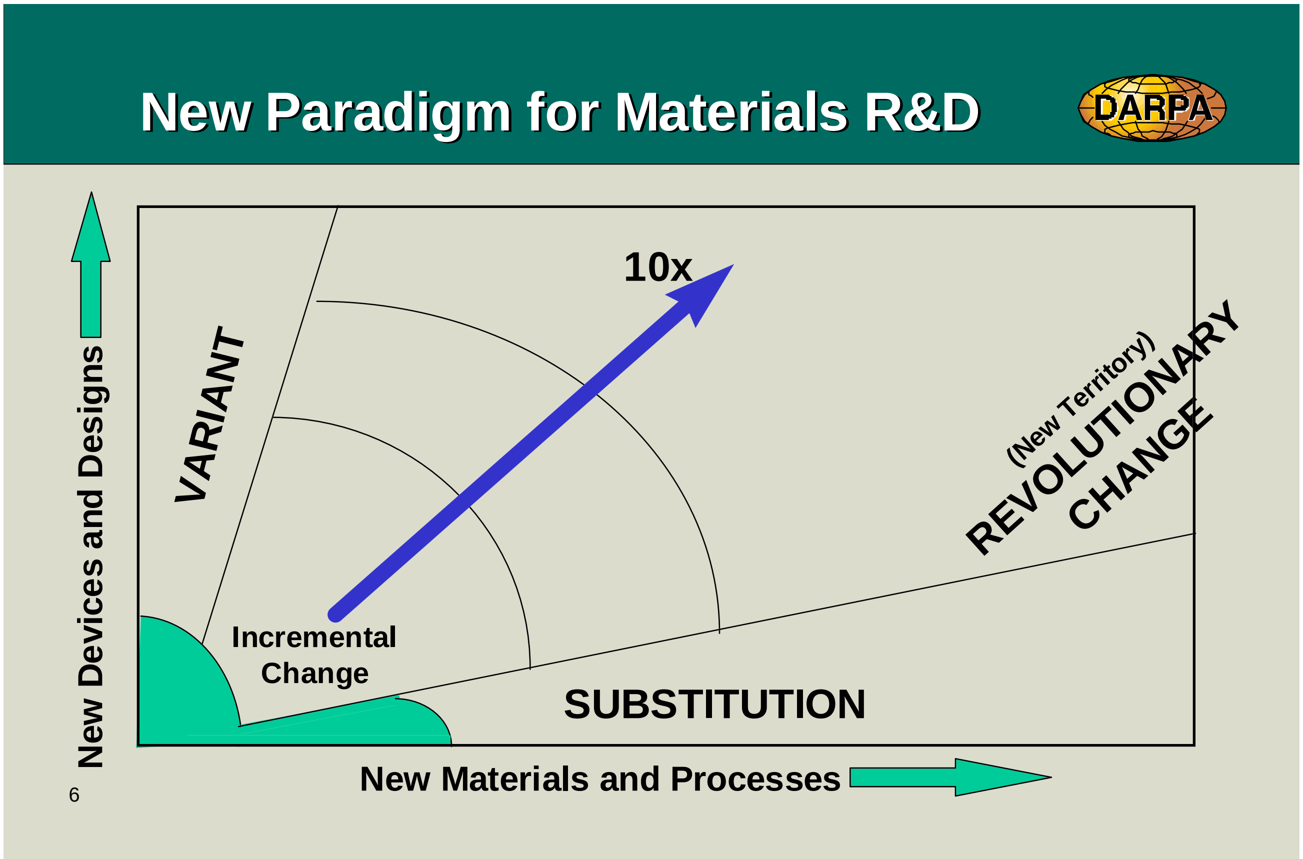
It is useful to begin with the overall strategy by which DSO has been evolving its materials program over the last several years. There are two driving forces for the program. The first is an attempt to meet emerging DoD needs. This simply says R&D that is done by DARPA now is aimed at impacting systems and system concepts in 5 to 10 years or more. This chart shows examples of such trends, none of which should be surprising. The second driving force is based on DARPA's ability to take some risks and the desire to apply critical mass to materials technology. Thus, programs of interest are those which change the way one thinks about the development and use of materials. These are also shown on this chart.



This chart is very schematic but depicts what is meant by changing the paradigm of materials development. Typical materials development is done by evolutionary changing of materials in existing designs. This leads to incremental improvements. Likewise, changes in design are most often done with existing materials – again leading to incremental improvement. What DARPA's program is trying to do is to couple those two factors so that one makes a revolutionary change in capability.

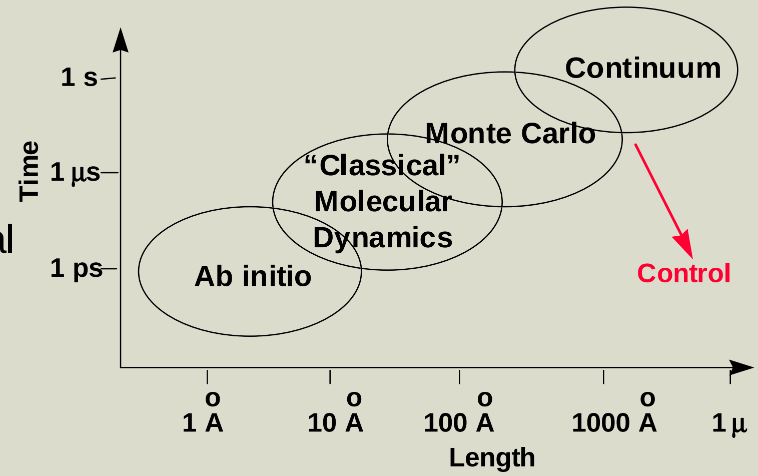
Virtual Integrated Prototyping

DARPA

Integrated Process, Sensing, & Control Models

Effective Computational Methods

Reduced Models



"Virtual" Process Development

- Faster, More Cost Effective Scale-up Strategies
- Higher Yields

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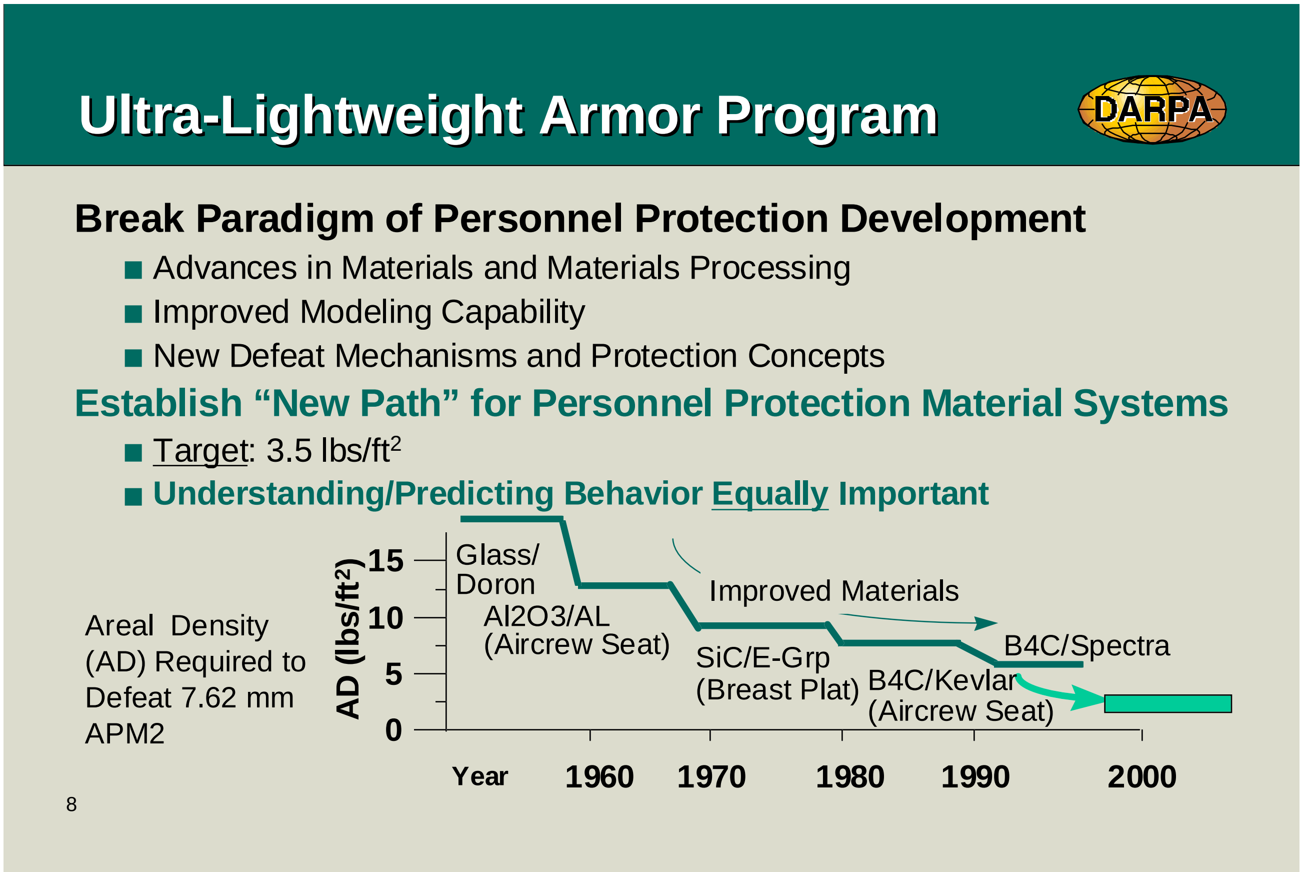
In the same way, there are large gains to be made if one could eliminate or greatly reduce the trial and error in materials processing. One such way to do that is to harness the power of mathematics to make a significant difference in the way materials systems are modeled. Each level of modeling can provide insight into the process, but has constraints due to assumptions and/or the complexity of the calculations. By applying the tools of mathematics, the hope is to tie these together to maximize one's ability to predict, as close to first principals as possible, the behavior of materials in the processing environment.

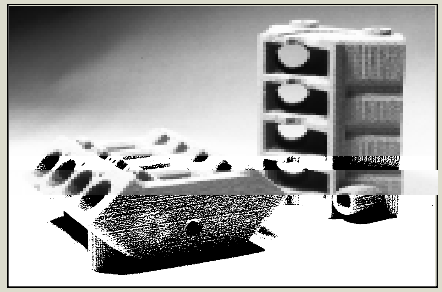


The remainder of the talk will describe some of the highlights of the program. Hopefully this will provide a demonstration of the strategy as well as providing some insight into where the opportunities are. The first project is one that has just gotten underway in personnel protection. This is an example of a program to change the way personnel armor is formulated by combining materials science and design. Previous gains have been made by using new materials, making for lighter systems. But these systems see limited use because they are still too heavy. The DARPA program, working in conjunction with the U.S. Army Soldier Systems Command in Natick, Mass., will use modeling and advances in materials concepts to look at new defeat mechanisms and protection concepts.

Solid Free-form Fabrication and Design

DARPA

Extend Machine Capabilities



- New Materials and Combinations
- Improve Dimensional Tolerances and Surface Finish
- Positional Control of Composition and Texture

Integration of Concurrent Engineering Capabilities

- Code to facilitate exchange of key material and SFF process information
- Supporting design optimization software

Rapid Prototype Demonstrations

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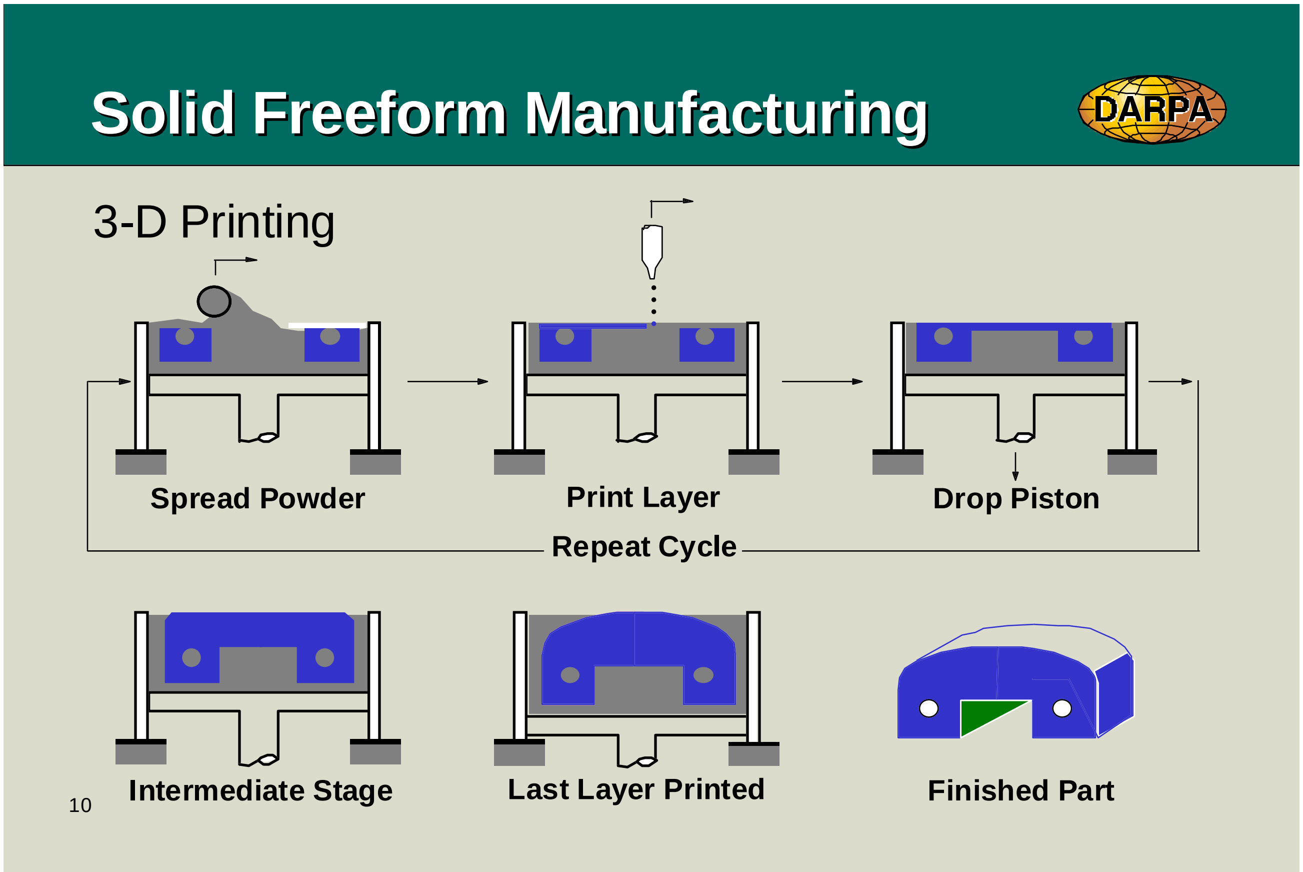
Another area of technology which continues to provide both payoff for defense and additional opportunities is the area of Solid Freeform. There are a number of techniques being developed, but in general they all have the attribute that they develop parts layer by layer from computer files. An example of this technology, 3-D printing, is shown on the next chart. This technique allows for the first time the coupling of sophisticated design techniques, much like described previously and the development of new materials.



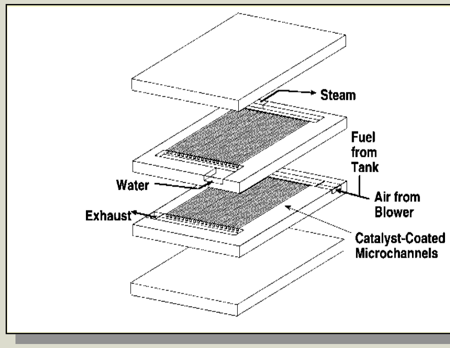
An example of the solid freeform fabrication of an arbitrary component based on 3-Dimensional printing is shown here. This technology was developed at MIT. It is a very simple process yet allows very complex shapes to be fabricated very quickly. First, a thin layer of powder is spread uniformly on a piston. An ink jet printer head filled with binder is then rastered across the surface. A computer generated CAD file controls the firing of the head. The piston is then dropped and the process is repeated until the part is completed. The ultimate resolution is determined both by the particle size of the powder and by the drop size and flow characteristics of the binder. The MIT group has used this technique to build a ceramic turbine nozzle in only 30 minutes!

Mesoscopic Machines

DARPA

Enhanced Heat, Mass, Momentum and Electron Transport Properties

Optimal Size Range For a Wide Variety of Chemical Reactions and Fluidic Functions



Mesoscopic Systems

"Sugar cube to fist"

1 nm | 1 µm | 1 mm | 1 m | 1 km

Microelectro-mechanical Systems

Transistor/IC

Sensors/Actuators

Pumps/Valves

Reactors/Heat Exchangers

Thermal Chemical Plants

Conventional Systems

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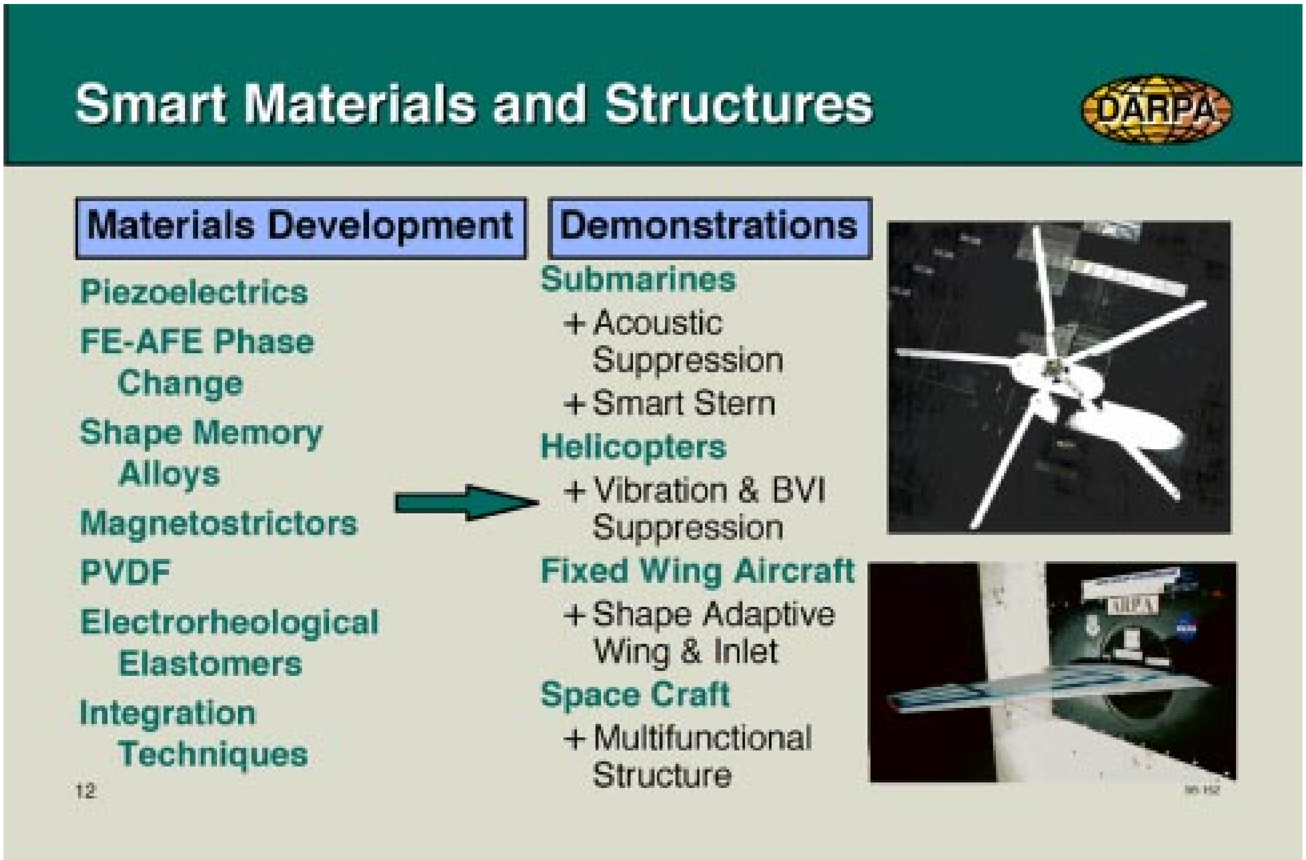
It has been observed that there are some significant advantages for working at what is called the "mesoscopic" range. These include enhanced heat and momentum transfer. In addition, this scale is optimal for a wide range of chemical reactions and fluidic functions. It is the ability to "design" materials with more capability and at finer scale as just described that has led to the opportunity to provide some interesting devices for Defense. Several programs are now underway in this area, demonstrating devices such as miniature pumps for portable biosensors and coolers for the individual soldier. Additional efforts are expected in the next year or so.



The Smart Materials and Structures program has been one of the strengths of DARPA's materials program for several years. This program has advanced the development of actuators materials and, more recently, has demonstrated the use of these in specific Defense applications. Among those is the use of the smart materials to suppress vibrations in both submarines and helicopters. In addition the use of smart structures to adapt a wing shape to significantly reduce drag has also been demonstrated.

High Authority Actuators

DARPA

Single Crystal Perovskites

Polymeric Muscles

High Performance SMA

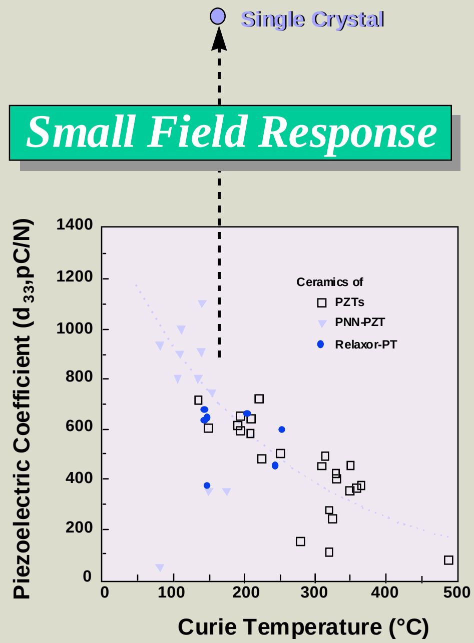
Magnetically Actuated SMA

Active Fiber Composites

Terfenol Optimization

Injection Molded Actuators

Relaxor Ferroelectric Actuators



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However, as successful as these demonstrations are, they also point to the need for higher authority actuators. And, one of the more promising developments in that area are single crystal Perovskites which have shown up to 10 times the strain capability and a factor of two greater coupling efficiency. The exploitation of these will be a major future thrust at DARPA.

Adapted Biological Systems

Mine Location, Aquatic Patrol, Effluent Monitoring, Homing and Tagging

"Robolobster"

- **Maintains Stable Locomotion in Strong Current and Wave Action**
- **Omnidirectional Movement**
- **Low Power Requirement and Efficient**

- **Biological Strategies for Compensation, Movement, Power Efficiency**
- **Develop and Integrate: Actuators, Sensors, Power and Controller**
- **Test Prototype Under Littoral Condition**

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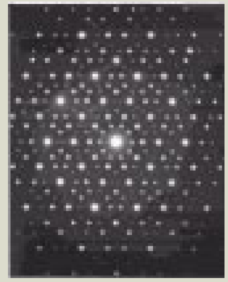
In some sense, the epitome of a smart structure is one which emulates real "intelligence" of biological creatures. To that end, DARPA is looking at technology to emulate the adaptability of biological creatures using robotics. "Robolobster" is just such an example. While much of the problem is capturing the specific neurological behavior and translating it to motion, the actual building of the robotics turns out to be a non-trivial task with very critical material science issues. One can think of employing the same technologies as used in the mesoscopic machines and the smart materials program.

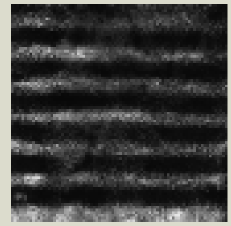
Novel Materials Structures

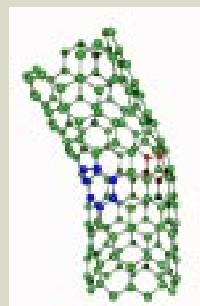
Examine Novel Material Structures

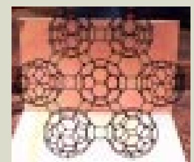
- Quasicrystals
- Carbon-Based Structures
  - Nanotubes
  - Fullerenes
- Multilayered Structures
- Mesoporous Materials
- Nanoparticles
- Self-Healing Materials

Exploit for Defense Applications









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The last few charts present some of the opportunities which have yet to be totally fleshed out, but may well fit into the DARPA Strategy outlined. This chart shows a number of materials concepts which are currently being examined extensively in the basic research community. With few exceptions, most of these materials remain curiosities, with most of the work aimed at understanding the properties. It might well be that the time is ripe for looking at whether any of these could be used to solve a specific Defense problem.

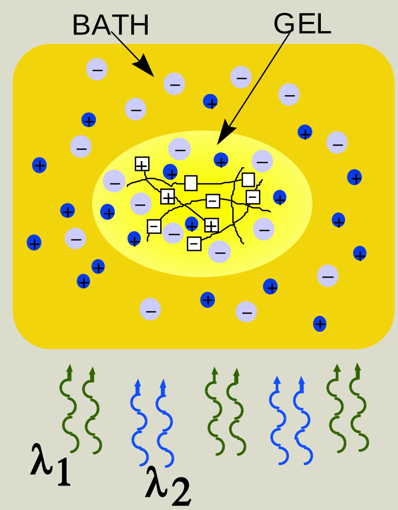
Electroactive Polymers

Engineered Microstructure

- Engineer Band Gap (1-4 eV)
- Control Phase Stability
- Morphology
- Interfacial Interactions

Tailor Surface Properties

- Impedance
- Transmission



Rapid Image Processing
EM Signature Control
Smart Structures
Smart Camouflage
Chemical/Biological Sensors

λ_1 Wavelength to change pH 5 -> 2

λ_2 Wavelength to change pH 2 ->5

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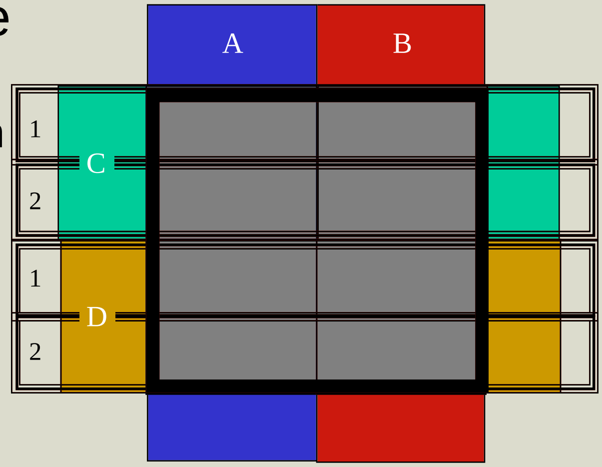
Less speculative, but still of great challenge, is the use of electroactive polymers. The idea would be to control the chemistry and microstructure of these polymer to exactly control their electronic properties. One can then envision complete electronic circuits in a thin sheet of plastic.

Combinatorial Synthesis

Rapid Synthesis, Evaluation of Complete Combinations

- Traditionally Composition Dependent Properties
- Pharmaceuticals

Application to More Complex Materials Problems To Be Explored



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And finally, the technique of Combinatorial Synthesis is being examined as a way to look at new and interesting materials. This would have the greatest impact in systems for which traditional trial and error would be impossible. Finding a room temperature superconductor might well fall into this category.

Summary

Materials Program Aligned with Emerging Defense Needs

Increasing Emphasis on:

- Functional Materials
- Rapid Design, Design Optimization
- Computation Techniques
- Microstructure Control

Likely Opportunities

- Single Crystal Actuators
- Frequency Agile Materials
- Electroactive Polymers
- Biomimetics
- Novel Materials

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In summary, the DARPA program is a dynamic one that remains responsive to defense needs while still exploring the limits of materials science. This chart shows the many opportunities which will be emerging in the next year or so.